Design and Performance of a High Brightness Pulsed Power Electron Source

John Smedley, Triveni Srinivasan-Rao, Thomas Tsang, Ilan Ben-Zvi
BNL

J. Paul Farrel, Ken Batchelor
Brookhaven Technology Group

Overview

- **Motivation**
- **Design**
  - **What is a Pulsed Gun and Why is it Interesting?**
    - **Scaling Laws (Emittance, Current & Brightness)**
    - **Simulation Results of Beam Characteristics**
  - **Production of the HV pulse and synchronization**
    - **High voltage pulse generator**
    - **Laser Triggering**
- **Performance**
  - **Characterize Dark Current and Breakdown Threshold**
  - **Photoemission Measurements**
  - **Measurement of Beam Energy**
  - **Emittance & Energy Spread (Future Plans)**

What is Brightness?

- Beam Brightness: The number of electrons per unit volume of phase space
- Techniques to increase brightness
  - Increase Beam Charge
  - Reduce Pulse Duration
  - Decrease Emittance
- Applications of High Brightness Electron Beams
  - High Brightness (short pulse duration) X-Ray Sources
  - Free Electron Lasers

RF Photo-Injector

UV Laser extracts electrons from a cathode inside an RF cavity

Electrons are accelerated by RF Field

Typical frequency range is 144 MHz to 17 GHz

Maximum field ~200 MV/m

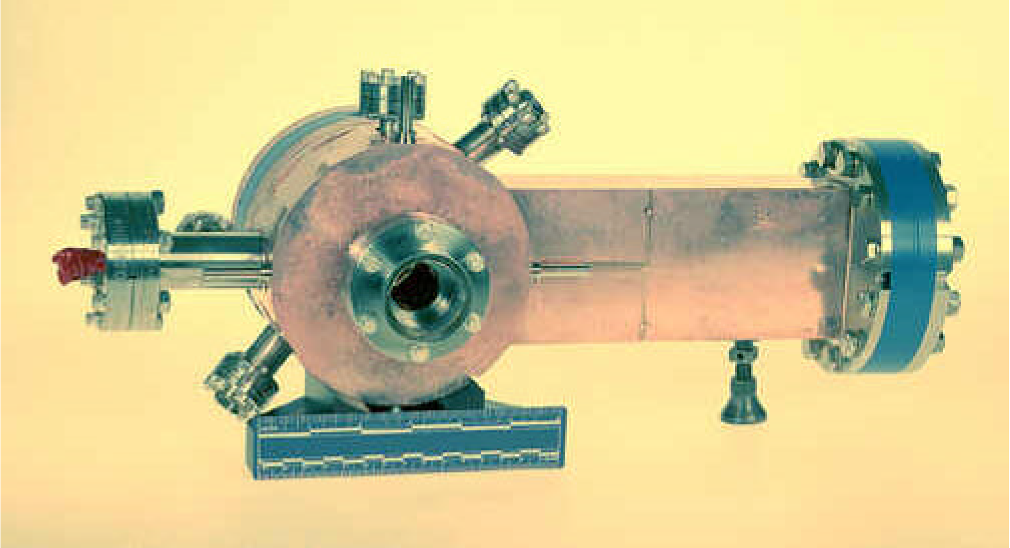
Bunch Charge 1 - 5 nC

Pulse Duration 1 - 20 ps

Emittance 1 - 5 π mm-mrad

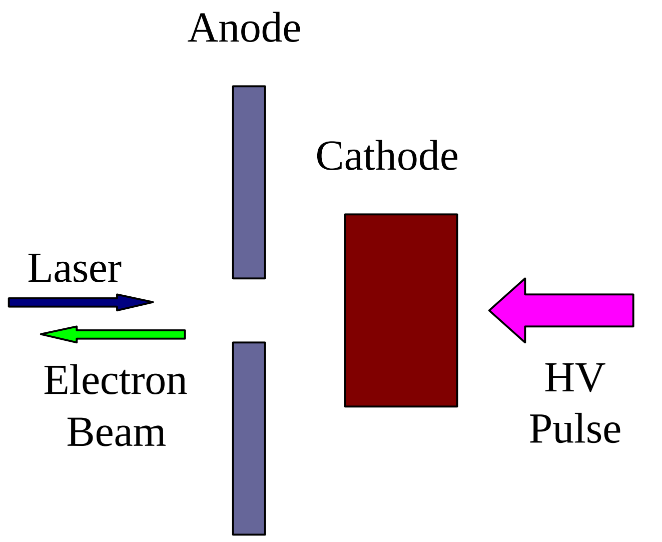
Maximum Brightness

4×10^{13} A/m^{2}rad^2



What is a Pulsed Gun?

- Parallel plate electrodes
- Short pulse allows gradients > 1 GV/m without breakdown
- HV pulse synchronized to the laser



Why is the Pulsed Gun Interesting?

- **Much Higher Gradients**
  - **Pulsed Guns can obtain 1 GV/m and higher**
  - **For RF Guns, maximum field :** $E_{0\max}[MV/m] = 8.47 + 1.57\sqrt{f[MHz]}$
- **Flat Temporal Distribution During Emission**
- **Investigate Scaling Laws For:**
  - **Emittance - Correlation between a particle's transverse position and transverse momentum**
  - **Maximum Extractable Current**
  - **Brightness**
- **Simulation**

Emittance

- **Emittance - Correlation between a particle's transverse position and transverse momentum**

$$e = \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x \cdot p_x \rangle^2}$$

- **Sources of Emittance**
  - **Thermal:**
    Randomly oriented initial energy
    $$e_T \propto \sqrt{(hn - f) + kT}$$
  - **Space Charge:**
    Self-Repulsion of electrons
    $$e_{SC} \propto \frac{Q}{E_0 (2s_x + s_z)}$$
  - **RF:**
    Temporal and spatial variation of electric fields
    $$e_{RF} \propto E_0 f^2 s_x^2 s_z^2$$
- **Total Emittance:**

$$e_{Tot} = \sqrt{e_T^2 + e_{SC}^2 + e_{RF}^2}$$

Ref: C. Travier, NIM, A340, 26 (1994)

Scaling Laws

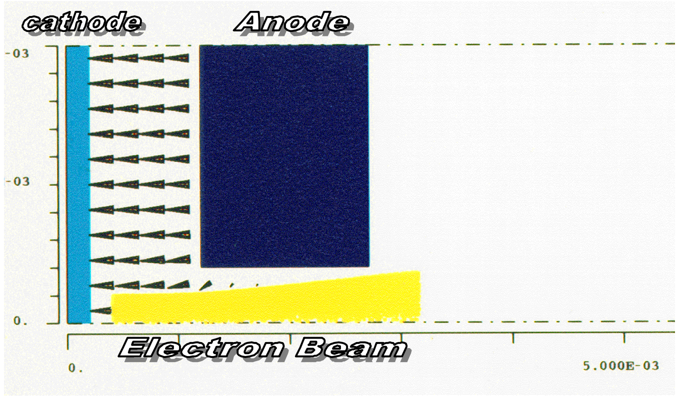
- **Emittance**
  - **Space Charge Contribution Scales as $1/E_0$**
  - **RF effect dose not apply to Pulsed Gun**

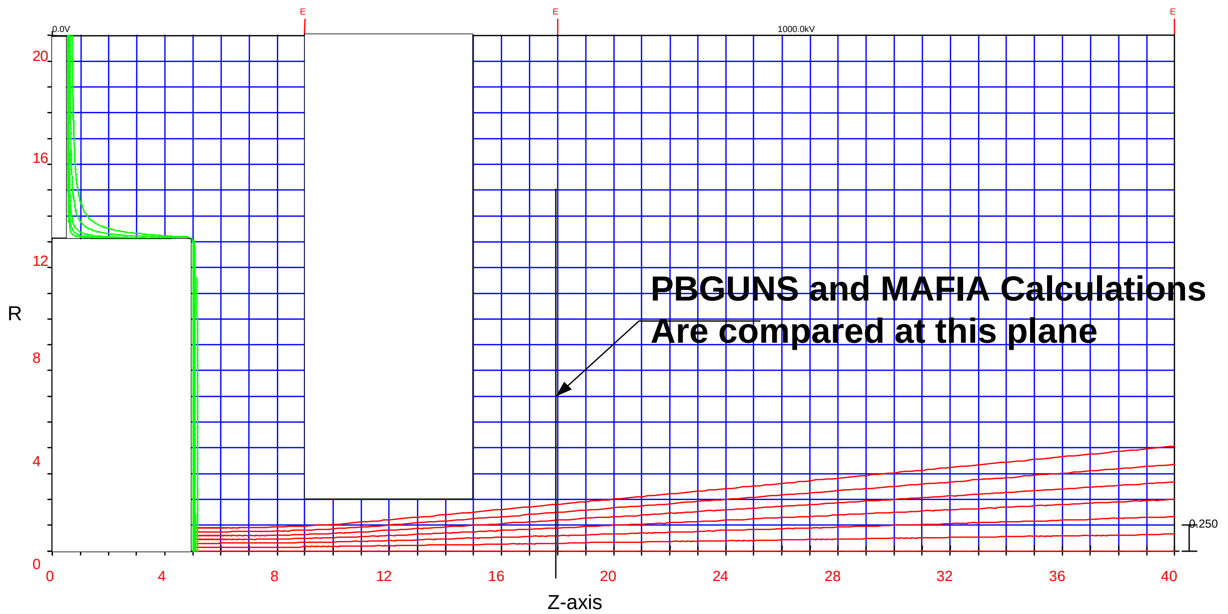
- **Maximum Current Density**
  - **For very high current densities, the accelerating gradient can be canceled by the space charge field**
  - **Governed by Child's Law: $J \propto (E_0)^{3/2}$**

- **Brightness**
  - **Brightness given by** $$B = \frac{2I}{e_{tot}^{2}}$$

Geometry for Simulation

- Used MAFIA and PBGUNS
- 1 mm gap
- 0.5 mm radius anode hole
- 0.25 mm emitting spot
- Uniform current density
- 1 MV potential, 1 GV/m gradient



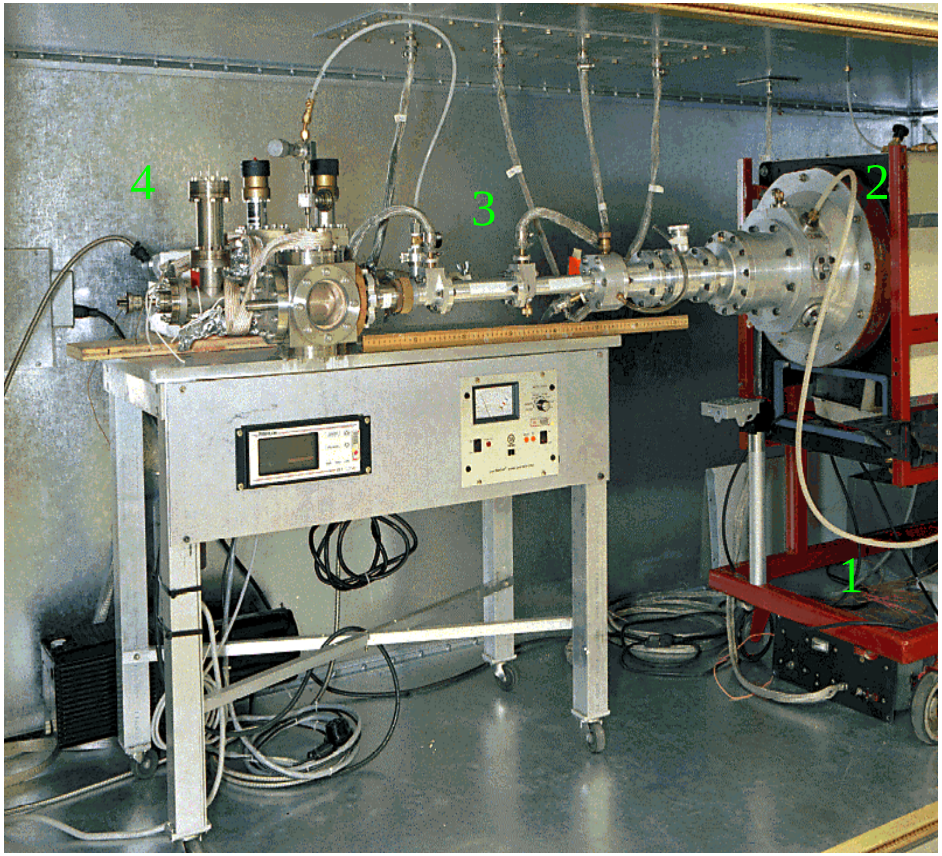


Simulation Results

- Emittance as a function of current and pulse duration
- Investigated effect of a 1 eV random initial energy
  - Contributes 0.17 π mm-mrad to total emittance
- Total beam emittance of 0.4 π mm-mrad for 100A, 10ps bunch
- Brightness of 1.3×10^{15} A/m^{2}rad^2
  - Compare to RF gun value of 4×10^{13} A/m^{2}rad^2
- Longitudinal energy spread of 0.15% for 100A, 10ps bunch
- Maximum Current of 750 A -> Current Density of 3.8×10^{5} A/cm^2

	PBGUNS		MAFIA		
CATHODE CURRENT Ampere	BEAM RADIUS mm	MAX DIVERG. mrad	BEAM RADIUS mm	MAX DIVERG. mrad	ε_n π mm-mrad
1	0.47	100	0.475	99	0.118
100	0.5	112	0.503	112	0.162
200	0.535	125	0.533	126	0.241
300	0.6	140	0.577	141	0.292
600	0.65	165	(+) 0.633	170	0.617
(*) 1000			(+) 0.707	173	2.16

1 MV Pulse Generator



Low Voltage System

- 500 nF Capacitors charged to 15 kV
- Triggered Spark Gap

Resonant Transformer

- 1:80 Ratio
- Laser Triggered SF_6 Spark Gap

Transmission Line

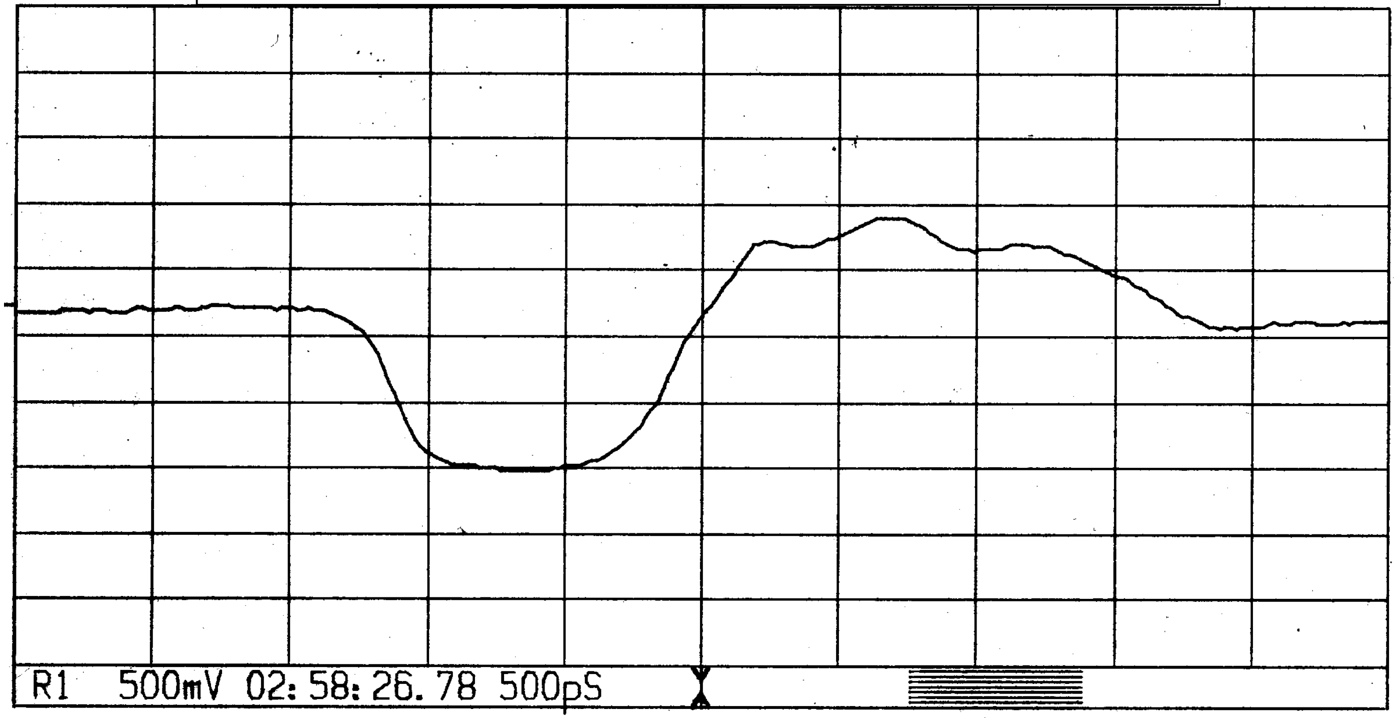
- Sharpens Voltage Rise and Fall
- Tapered Line Transformer

Vacuum Interface

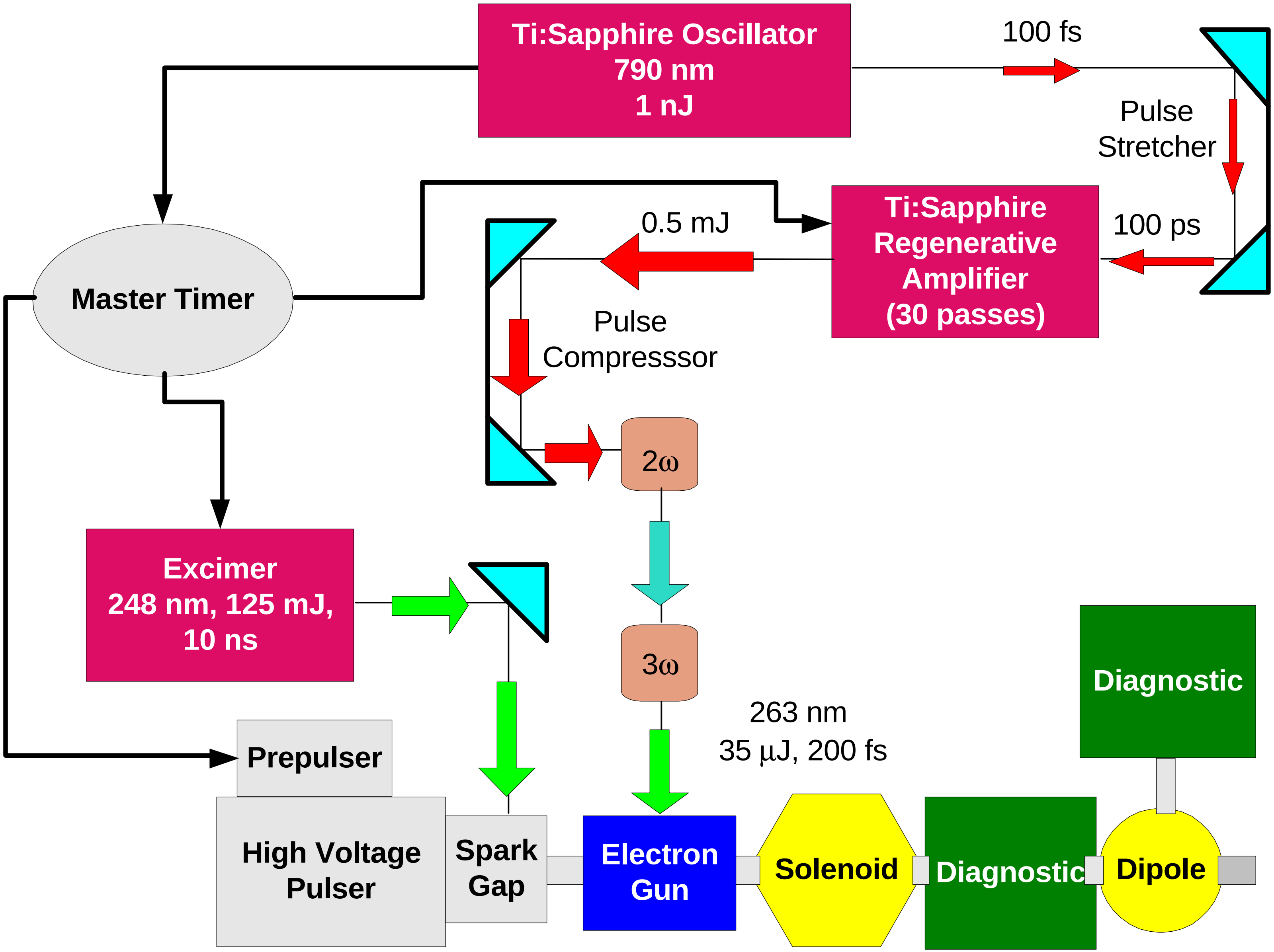
- Adjustable Electrode Spacing

Voltage Trace from MV pulser

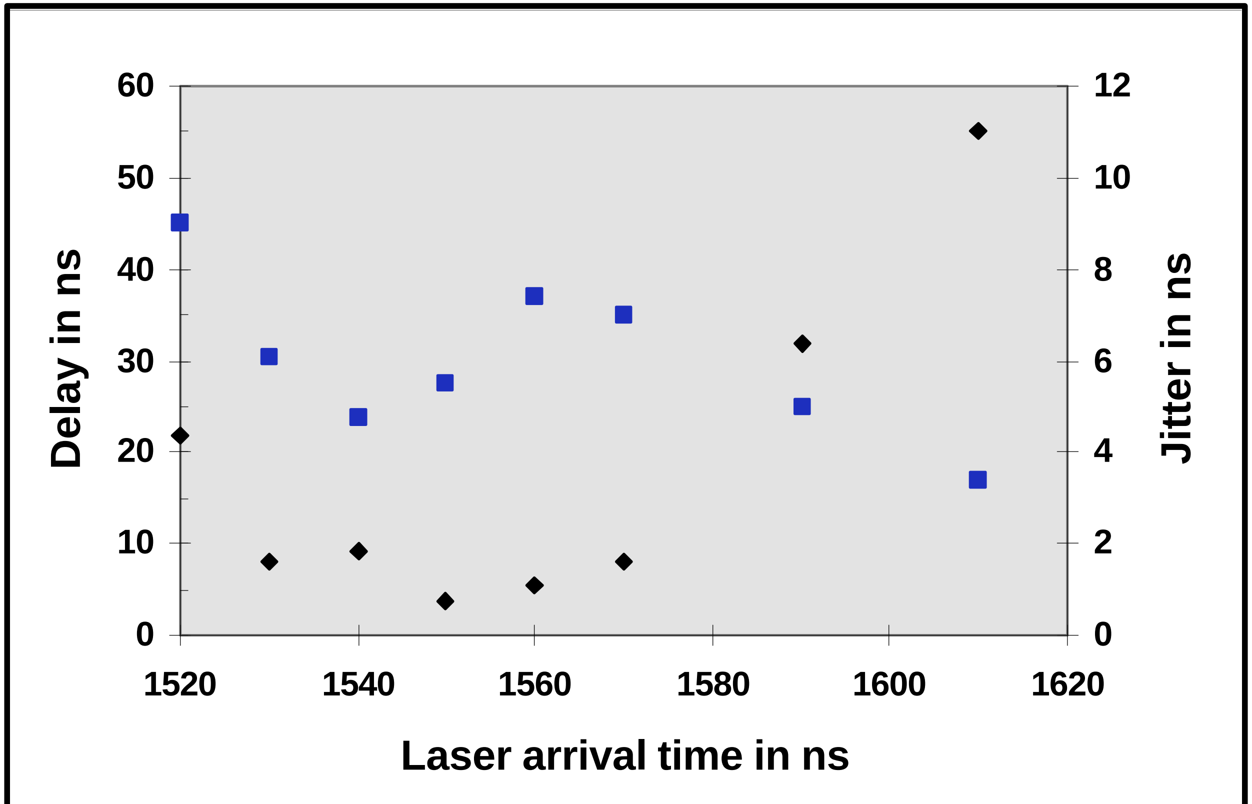
1 ns duration, with 100 ps rise and fall
Amplitude is 900 kV



1 MV Pulser System w/ Ti:Sapphire



Laser Triggering to Control Voltage Timing



- Timing Jitter ~15 ns w/o Laser Trigger
- KrF Excimer Laser used to control spark gap
- Best Jitter is ~0.5 ns
- 160 mJ of Laser Energy for 7 atm SF_6
- 90 mJ of Laser Energy for 5:2 mix of SF_6 and Argon

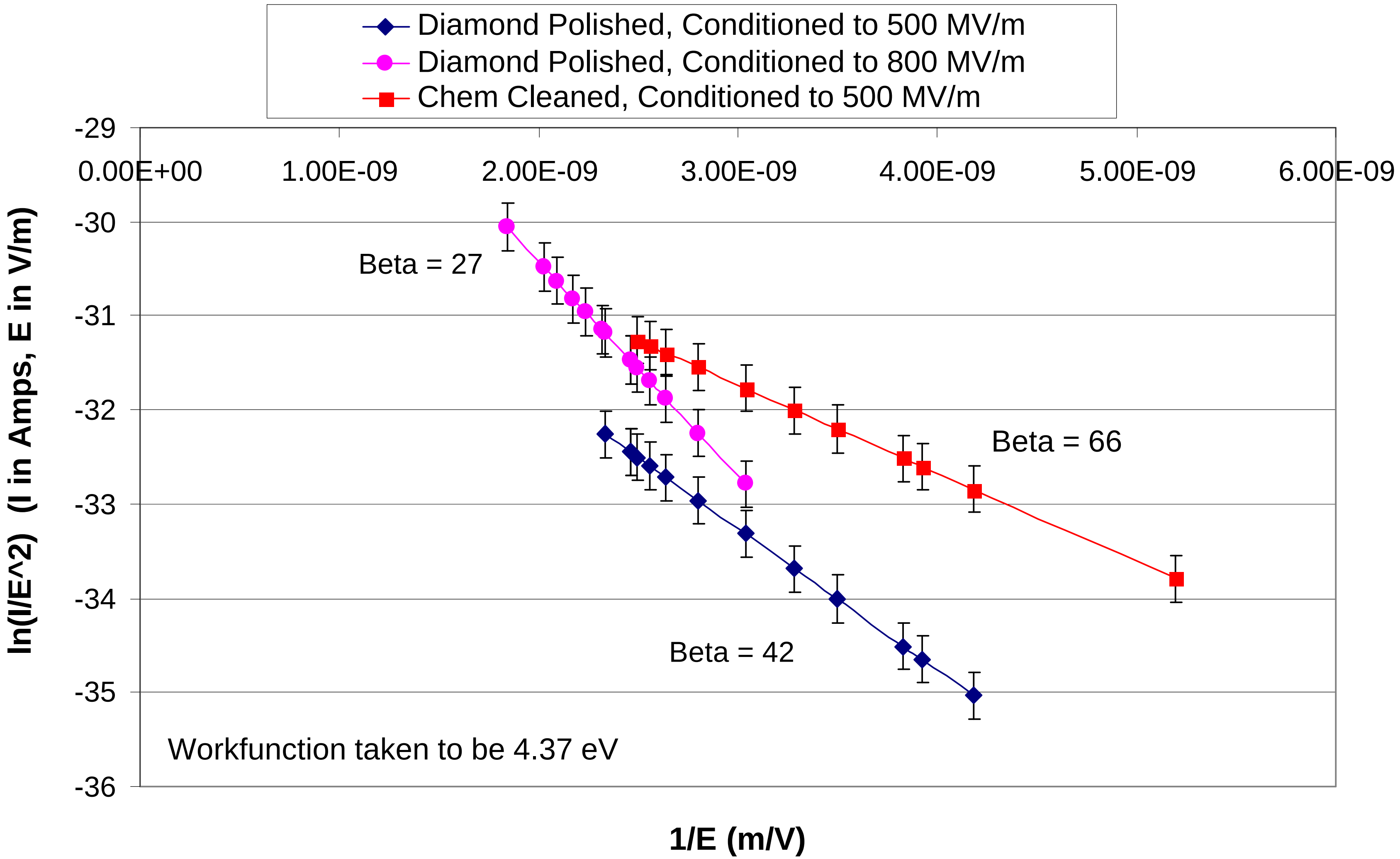
Field Emission

- Dark Current arises from electron tunneling
- Emission occurs at places of maximum field enhancement [tips, inclusions]
- Current Density defined by Fowler-Nordheim Equation:

$$J = \frac{1.54\times10^{-6}(b_{FE}E)^2}{f}\exp[\frac{-6.83\times10^{9}f^{3/2}}{b_{FE}E}]$$

- Common to plot : $\frac{1}{E}\, vs \ln[\frac{I}{E^2}]$
- Slope determines β_{FE} if ϕ is known
- Conditioning blasts off enhancement centers, reduces β_{FE}
- Surface preparation technique is very important

Fowler-Nordheim Plot for Cu Cathodes



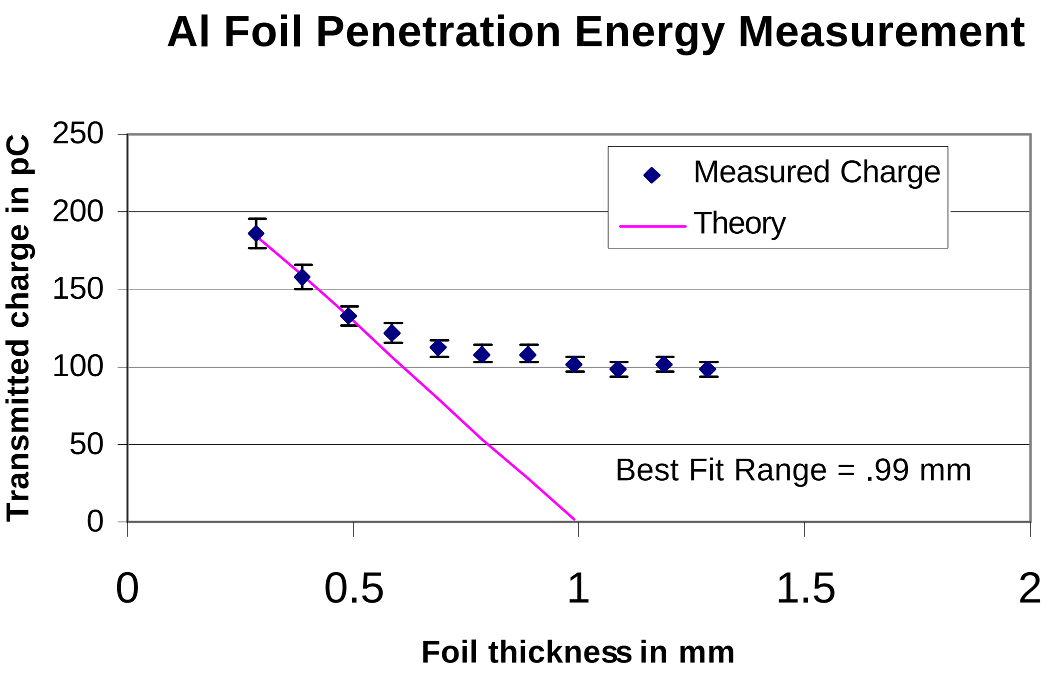
Field Emission Results

- Properly prepared cathodes can withstand fields in excess of 1 GV/m provided the pulse duration is ~ 1ns

- The dark current after conditioning can be reduced to under 5 pC at 500 MV/m

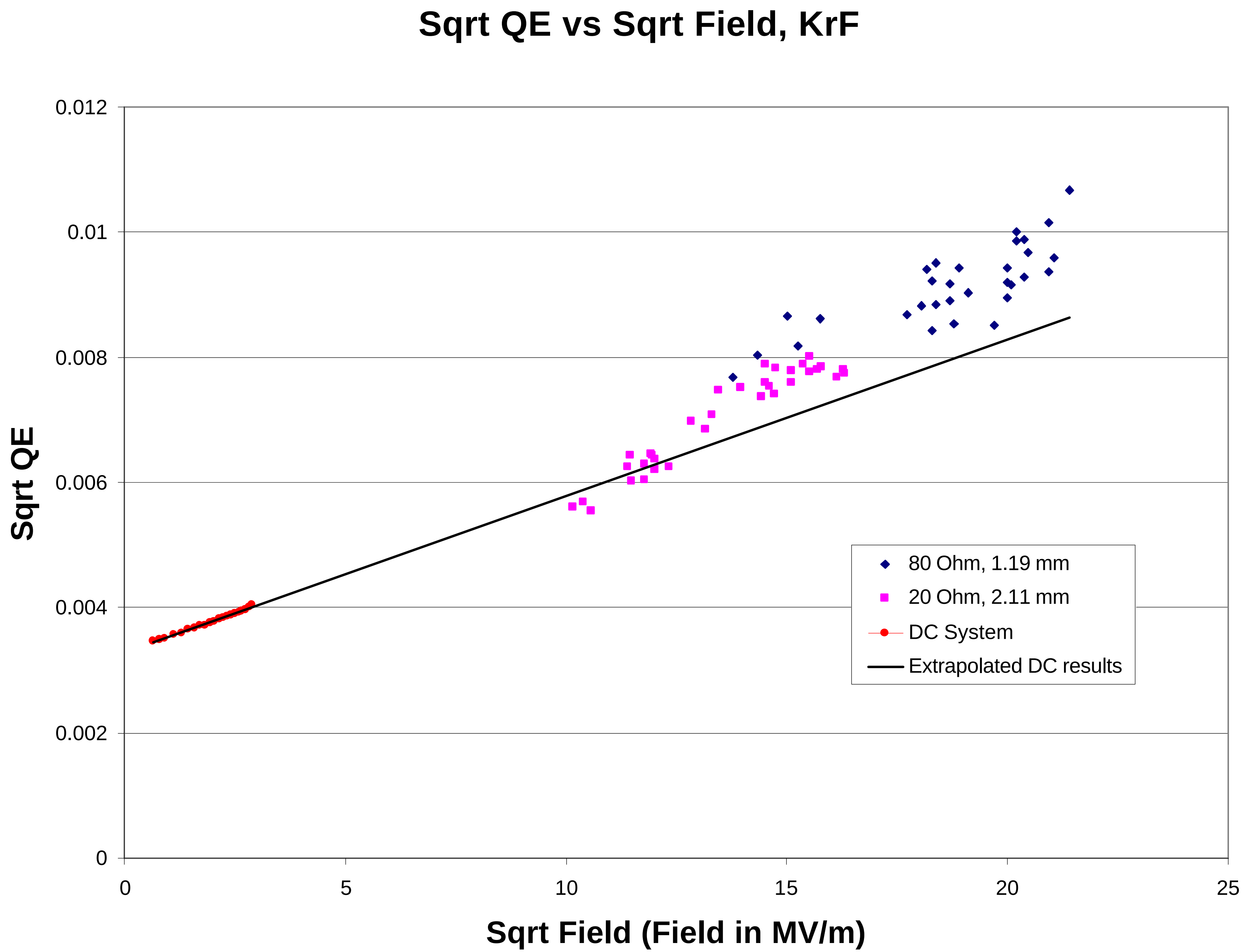
Electron Energy Measurement

- Transmission though Al foils measured
- Best fit range is ~1 mm
- Corresponds to 715 keV
- Input energy was 650 keV



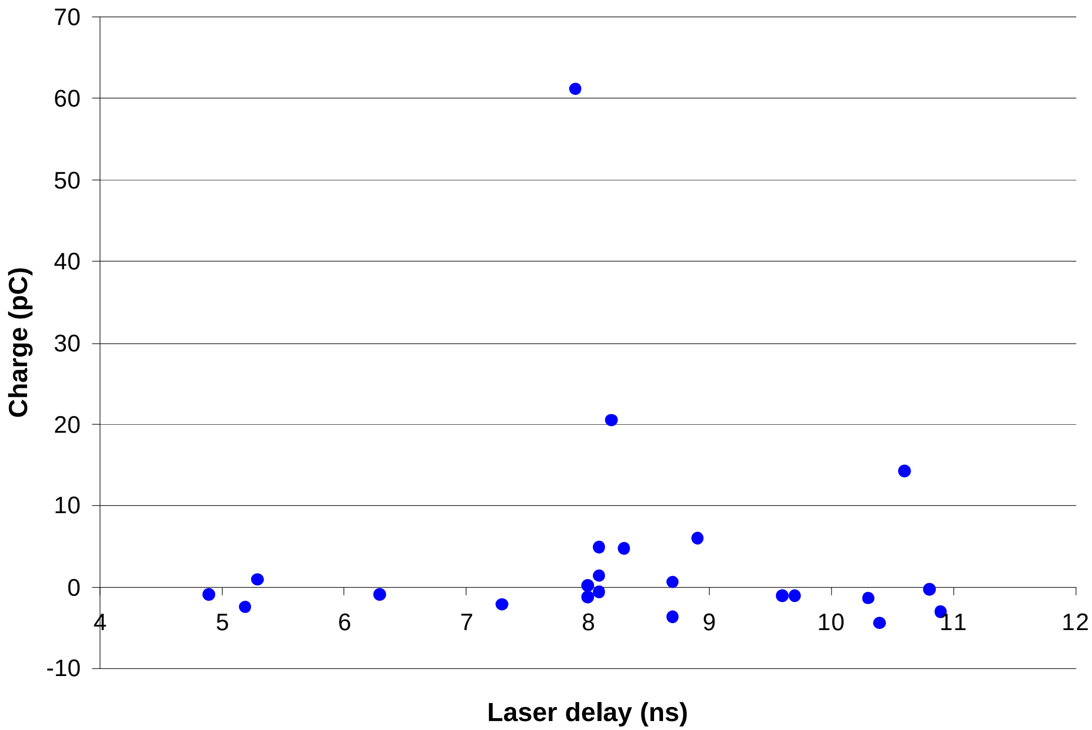
Photoemission w/ KrF

- Laser Parameters - 60 μJ in 23 ns pulse, 248 nm
- Corresponds to ~0.6 μJ during the voltage pulse
- Measured charge: 12 pC
- Quantum Efficiency: 10^{-4} at 500 MV/m
- Field Dependence of the QE
  - For small values of (hν−φ): $QE(n) \propto (hn - f)^2$
  - Schottky Effect: $f = f_0 - \sqrt{\frac{\mathrm{eE}}{4pe_0}}$ -> $QE \propto \left(\mathrm{h}n - f + \sqrt{\frac{\mathrm{eE}}{4pe_0}}\right)^2$
  - This implies that a plot of $(QE)^{1/2}$ vs $[\text{Field}]^{1/2}$ will be linear



Sqrt QE vs Sqrt Field, KrF
0.012
0.01
0.008
0.006
0.004
0.002
0
Sqrt QE
0
5
10
15
20
25
Sqrt Field (Field in MV/m)
80 Ohm, 1.19 mm
20 Ohm, 2.11 mm
DC System
Extrapolated DC results

Photoemission with 250fs Ti:Sapphire



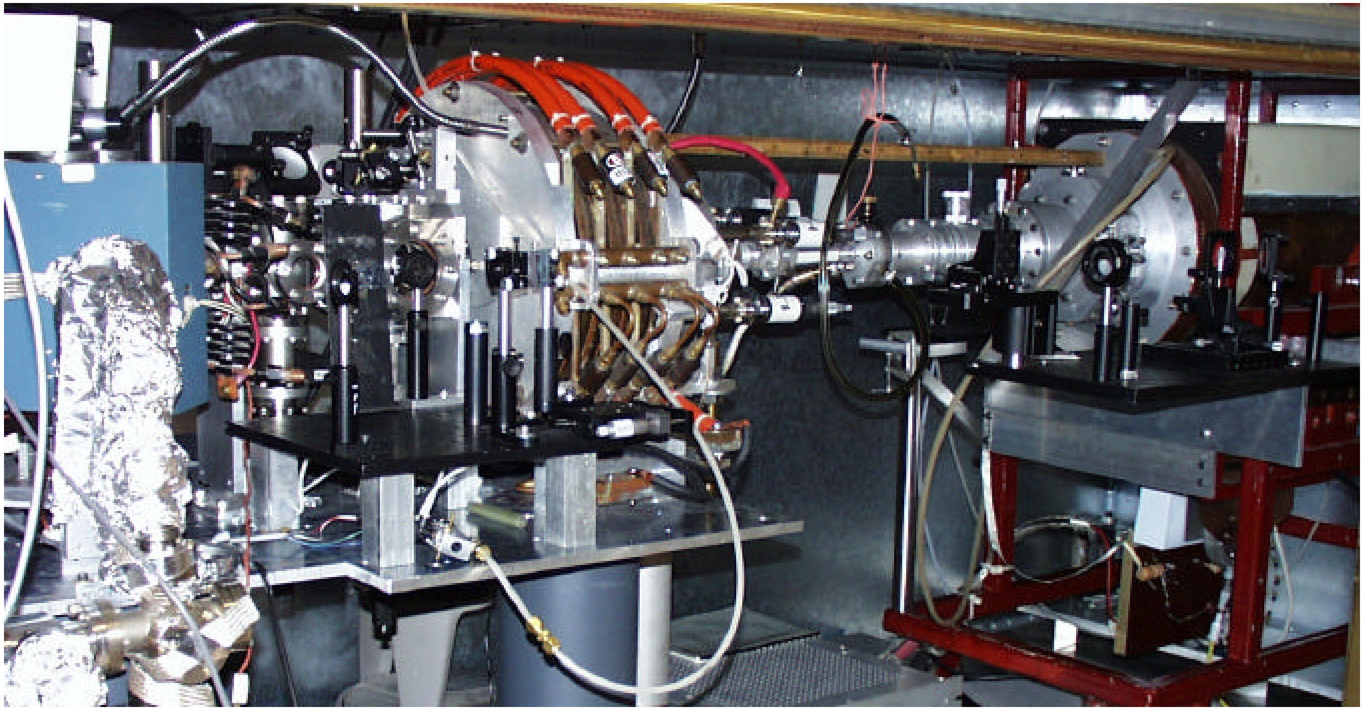
Cathode Laser

- Ti: Sapphire 3rd Harmonic, 266 nm
- Pulse duration after regenerative amplifier - 200-250fs
- 45 μJ on cathode

Measured Charge

- 60 pC measured charge
- Quantum Efficiency = 6.2E-6

Emittance and Energy Spread [Future Plans]

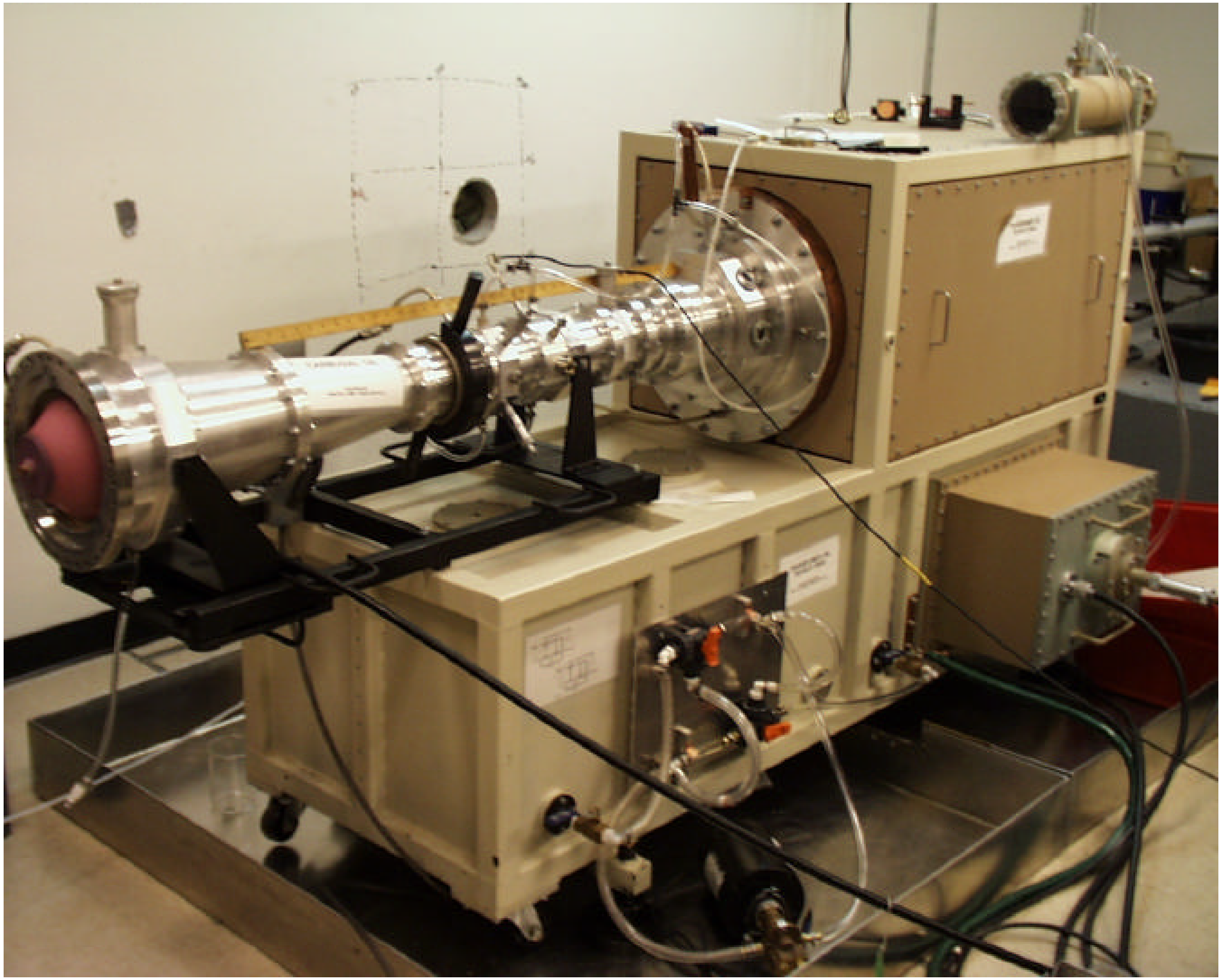


- A Solenoid Focusing Magnet and two Beam Position Monitors [BPM] have been installed for measurement of emittance
- A Dipole Bending Magnet and a final BPM have been installed for measurement of energy and energy spread

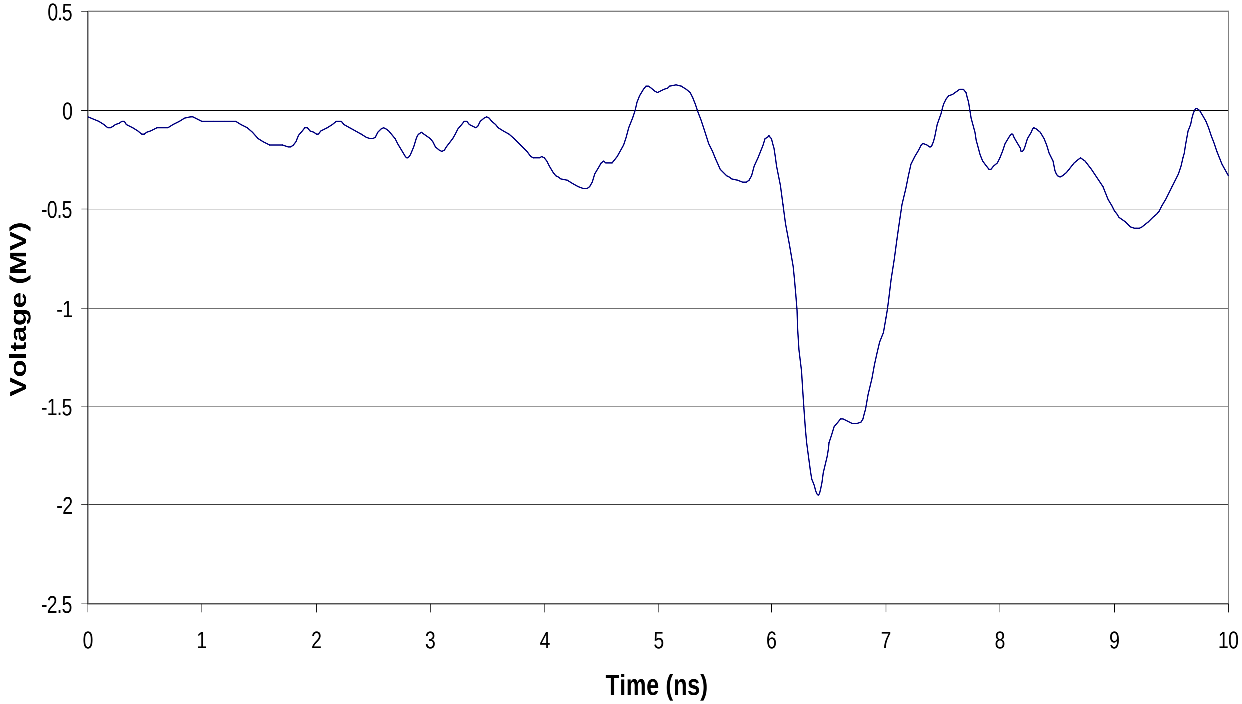
Conclusion

- Operation of a pulsed power gun to field gradients exceeding 1 GV/m has been achieved w/o breakdown
- Several cathode preparation techniques have been tested
- Synchronization to a trigger laser within 0.5 ns via laser triggering
- Photoemission has been achieved at fields up to 0.5 GV/m
- The Schottky effect describes the field dependence of photoemission over a large field range (0.5 MV/m to 0.5 GV/m)
- Simulations predict that a 100A, 10 ps beam with a full beam emittance of 0.4π and an energy spread of 0.15%
- Hardware for measurement of emittance, energy and energy spread has been installed and is being tested

Photograph of 5 MV Pulser

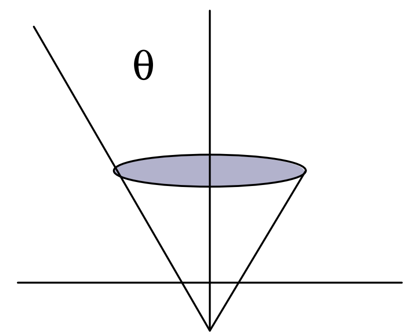


Temporal Profile of Voltage Trace at the End of the Impedance Matched Transmission Line



Escape Probability

- **Criteria for escape:** $$\frac{\hbar^2 k_\perp^2}{2m} > E_T = E_f + f$$



- **Requires electron trajectory to fall within a cone defined by angle:**

$$\cos q = \frac{k_{\perp \min}}{|\vec{k}|} = (\frac{E_T}{E})^{1/2}$$

- **Fraction of electrons of energy E falling with the cone is given by:** $$D(E) = \frac{1}{4p}\int_0^q \sin q' dq' \int_0^{2p} dj = \frac{1}{2}(1 - \cos q)$$
- **For small values of E-E_T, this is the dominant factor in determining the emission. For these cases:** $$QE(n) \propto \int_{f+E_f}^{hn+E_f} D(E)dE = \int_{E_T}^{(hn-f)+E_T} D(E)dE$$
- **This gives:**

$$QE(n) \propto (hn - f)^2$$